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NAVAL HEALTH RESEARCH CENTER

EVALUATION OF INFRARED THERMOMETRY OF TYMPANIC CAVITY AS AN INDICATOR OF CORE TEMPERATURE

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Report No. 94-3

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BETHESDA, MARYLAND

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Report No. 94-3, is supported by the Naval Medical Research and Development Command, Department of the Navy, under NSWC Reimbursable. The views expressed in this article are those of the authors and do not reflect official policy or position of the Department of the Navy, Department of Defense, or the U.S. Government. Approved for public release, distribution unlimited.

SUMMARY

Problem

Monitoring core body temperature in extreme environmental conditions is important in determining the level of heat strain and the effectiveness of clinical countermeasures. Traditional techniques of monitoring rectal (T_r) or esophageal (T_e) temperatures using thin, flexible wires attached to thermocouples or thermistors are not practical in field situations. The ease of monitoring tympanic temperature using infrared thermometry as a measure of core temperature is a powerful argument for its use in field situations to evaluate heat stress and effectiveness of various cooling methods. However, whether infrared thermometry of tympanic temperature (T_{ty}) accurately represents core temperature in exercising subjects is debatable.

Objective

The primary objective of this research was to monitor T_{ty} with an infrared detector while modifying either the environmental condition or the exercise state of the subjects to ascertain whether T_{ty} would show a similar response as traditional measurements of core temperature (e.g., rectal or esophageal).

Approach

T_r, T_e, T_{ty} and skin temperature (T_{sk}) (facial/neck) were recorded on 11 subjects under the following sequential conditions: (A) seated at rest in room temperature (20° to 22°C) for 20 min; (B) seated at rest in a climatic chamber (48° to 51°C) for 30 min; (C) performing exercise on a cycle ergometer at 100W in a climatic chamber (48° to 51°C) for 20 min; and (D) seated at rest in room temperature (20° to 22°C) for 10 min. In the final 4 min of conditions A, B, and C, ice packs were applied for 1 min to the left side of the zygomatic/maxillary aspects of the face and the sternocleidomastoid muscle of the neck. In condition A, immediately following ice application for 1 min, the same facial and neck areas were subjected to warm air currents (32.2 ± 2.8°C) for 1 min. In condition D, the left side of the face on 4 subjects was exposed to room air currents for 10 min.

Results

During rest in the normothermic condition (condition A), T_{ty} correlated with T_r and T_e. In this condition, localized facial cooling and heating had no effect on the temperature at the three sites. In condition B, when subjects were seated in a hot climatic chamber (48° to 51°C) all recorded sites demonstrated temperature increases. However, the T_{ty} readings remained consistently higher than T_r and T_e readings ($p < 0.01$). Localized cooling of the face and neck had no effect on the rate of rise of the three temperature sites. During the exercise condition in a hot climatic chamber (48° to 51°C; condition C), T_{ty} remained consistently higher than T_r and T_e ($p < 0.01$) and T_{ty} and T_{sk} readings decreased in response to ice application to the face whereas T_e and T_r were unaltered. When the subjects exited the chamber, T_e and T_{ty} decreased, whereas T_r continued to rise. Outside the chamber, exposure to air currents produced by a fan resulted in temperature decreases for all sites; however, the only statistically significant changes were observed in T_{ty} readings. Both the rate and value of the decreases in T_{ty} were greater when subjects were exposed to the wind currents, in comparison to those subjects not exposed.

Conclusions

The findings suggest that infrared thermometry of the tympanic canal does not satisfactorily estimate body core temperature under high heat conditions. Data from literature suggest that T_{ty} decreases with localized facial cooling. This was not initially observed in these studies. In addition, significant differences between T_{ty} and other temperature sites classically considered core sites were observed under exercise and rest in high heat, suggesting that T_{ty} does not consistently reflect core temperature, particularly in thermally stressful conditions. Use of infrared thermometry of tympanic canal for evaluation of heat-stressed subjects and effectiveness of various clinical countermeasures is not supported by these studies.

INTRODUCTION

Effectively monitoring body core temperature in thermally stressful environments can determine the level of heat stress the body sustains and direct the clinical countermeasures needed to reverse the heat stress. Rectal (T_r), esophageal (T_e), and tympanic (T_{ty}) temperatures are commonly used as estimates of core temperature. However, the one that best reflects body core temperature remains unresolved. T_{ty} is highly controversial as a measure of core temperature (Brengelmann, 1993; Cabanac & Brinnel, 1993).

In 1959, Benzinger proposed that the tympanic membrane was the principal site for measuring core temperature (Benzinger, 1959). Due to the proximity of the vascular supply to the tympanum, Benzinger proposed that T_{ty} measurements accurately represented arterial (core) blood temperature. According to Gray, the tympanum's blood flow arises from small vessels of the external carotid artery (Gray, 1901). Advocates of T_{ty} as a measure of core temperature adhere to the hypothesis that T_{ty}, rather than T_r and T_e, best reflect the thermal responses to hyperthermic conditions (Cabanac & Brinnel, 1985). It has been suggested that T_{ty} might be a reflection of a countercurrent heat exchange between the arterial supply to the tympanum and the adjacent venous blood flow (Nielsen, 1988). The T_{ty} may also indicate a countercurrent exchange between cool blood from the head and face and arterial blood supply to the brain (Cabanac & Brinnel, 1985; Cabanac & Caputa, 1979), or a reflex vasoconstriction in the arterial blood supply (Nielsen, 1988). However, it has been argued that T_{ty} does not represent brain temperature since it responds to changes in facial skin temperature indicating that T_{ty} merely reflects changes in peripheral temperature and circulation (Brengelmann, 1987).

The purpose of this study was to determine the relationship between T_{ty}, measured by an infrared detector, and T_r and T_e, using thermocouples, under heat stress during rest and exercise. In addition, we examined the effect of localized facial and neck cooling and heating at these three sites, since it has been reported that facial or neck cooling triggers a drop in T_{ty}. These skin temperature sites were chosen because in most cases of heat stress, the face or neck are cooled. Further, these comparisons were undertaken to determine if measuring T_{ty} with an infrared detector is practical for military field operations.

METHODS

Nine males (35.4 ± 5.4 years; 86.7 ± 8.8 kg) and two females (25.5 ± 2.5 years; 63.4 ± 2.1 kg) participated in this study after giving voluntary written consent. Procedures conformed to the guidelines of the Committee for the Protection of Human Subjects.

T_{ty} was recorded using an infrared detector which has an internal calibration capability (OtoTemp 3000, Exergen Corporation, Newton, MA). The same technician recorded all infrared detection readings to maximize measurement consistency. T_r and T_e were recorded using portable data loggers (Squirrel Digital Meter/Logger, Science/Electronics, Inc., Miamisburg, OH) and thermistor probes (Sheridan Catheter Corp., Argyle, NY). The esophageal thermistor probe was placed via the nasal route to approximately the level of the left atrium, then adjusted slightly for subject comfort. The left atrium and esophagus are in direct contact for several centimeters and are isothermal at this point (Brengelmann, 1987). The depth of insertion for all subjects was determined by a physician experienced in the placement of esophageal probes. The thermistor measuring T_r was inserted 20 to 25 cm past the anal sphincter. Temperature measures were monitored at 5- to 8-min intervals. T_{sk} on the left side of the face and neck were recorded using thermocouples (Yellow Springs Instruments, Inc., Yellow Springs, OH) and portable data loggers. Crushed ice, placed in plastic packs (6x6 in), was used for the ice applications. The ice packs were applied directly over the thermocouples on the face and neck for 1 min. For the facial temperature, the packs were placed on the left side of the zygomatic/maxillary area. For the neck temperature, the packs were applied over the sternocleidomastoid muscle. A portable heater (Bair Hugger, Augustine Medical, Inc., Eden Prairie, MN) with a hose attachment was used for the warm air applications. Subjects were required to place a bath towel over their heads, protecting their eyes, while a technician held the hose under the towel and directed the warm air toward the left side of the face and neck. The towel restricted the application of warm air to the localized areas of the face and neck. The air temperature was set at 32.2° ± 2.8°C for all subjects. Room air currents of 7.5 m/s were produced by a portable household fan placed approximately 5 ft away from each subject.

Procedures were performed under the following sequential conditions: (A) seated at rest in an ambient temperature of 20° to 22°C, (B) seated at rest in a climatic chamber with an ambient temperature of 48° to 51°C, (C) cycling on a stationary bicycle at 100W in a climatic chamber 48° to 51°C, and (D) again seated in an ambient room temperature of 20° to 22°C. Relative humidity was maintained at 20% in the climatic chamber. Air temperatures were controlled by eight radiant heat lamps and minimal convective air movements.

T_r, T_e, T_{ty} (left and right tympanic membranes), and T_{sk} (left side of the zygomatic/maxillary aspects of the face and on the sternocleidomastoid muscle over the carotid artery), as well as heart rate and blood pressure, were recorded at the end of each of the four conditions. In condition A, readings were taken in three phases: (1) control (no ice); (2) immediately (i.e., within 30 seconds) after 1 minute application of ice packs to the left side of the face and neck; and (3) immediately (within 30 seconds) after 1 min of localized heating of the left side of the face and neck. At the end of conditions B and C, T_{ty} readings were recorded before and immediately after ice application to the left sides of the face and neck. In condition D, temperature was recorded at the end of 10 min from 7 subjects (Table 1). Additionally, readings from the left and right tympanum were taken at 2- and 4-min from four different subjects in condition D who were exposed to a fan blowing on the left side of their face immediately upon removal from the chamber.

TABLE 1

Condition	T_r	T_e	T_{ty}-left	T_{ty}-right	T_{sk} Face	T_{sk} Neck
(A) Pre Chamber - Rest						
No Ice	37.1 ± 0.6	36.7 ± 0.4	36.7 ± 0.5	36.5 ± 0.4	33.6 ± 2.0	34.8 ± 1.6
Ice Application	37.0 ± 0.5	36.7 ± 0.4	36.6 ± 0.6	(*)	27.1 ± 2.6	29.2 ± 2.1
Heat Application	36.9 ± 0.5	36.7 ± 0.4	36.5 ± 0.4	(*)	33.6 ± 1.8	36.3 ± 1.2
(B) In Chamber - Rest						
No Ice	36.9 ± 0.5#	37.1 ± 0.3#	37.7 ± 0.5	37.9 ± 0.4	38.6 ± 0.8	38.3 ± 0.6
Ice Application	37.1 ± 0.4#	37.1 ± 0.3#	37.8 ± 0.5	(*)	30.3 ± 3.7	29.5 ± 4.1
(C) In Chamber - Exercise						
No Ice	37.7 ± 0.4#	37.7 ± 0.3#	38.4 ± 0.3 (**)	38.6 ± 0.3 (***)	38.7 ± 3.1	38.1 ± 1.0
Ice Application	37.7 ± 0.5	37.9 ± 0.6	38.1 ± 0.5	(*)	27.9 ± 2.8	28.3 ± 2.4
(D) Post-Chamber - Rest(**)	38.0 ± 0.3#	37.4 ± 0.5	36.6 ± 0.3	36.6 ± 0.2	33.0 ± 2.1	31.5 ± 3.8

(*) No Reading taken
(**) n=7
(***) n=6
Significantly different from $T_{ty\text{-}left}$ and $T_{ty\text{-}right}$ ($p<0.01$)
Mean $\pm$ SD

Analysis

Means and standard deviations were computed for temperature measurements during each of the four conditions, and t-tests were performed to evaluate the significance of mean differences. The level for statistical significance was $p<0.01$. Data are expressed as mean ± SD.

RESULTS

Table 1 shows the body temperature readings for all conditions. In the pre-chamber condition, the mean T_r, T_e, and T_{ty} remained constant with no significant differences. There was no effect on these three temperature sites 30 sec after application of ice and heat; however, both ice and heat had significant effects on the T_{sk} ($p<0.01$).

After 30 min at 48° to 51°C (condition B), mean temperatures for T_r and T_e had little or no increase, whereas both T_{ty} increased approximately 1°C ($p<0.01$). Throughout the 30-min interval, T_{ty} readings remained consistently higher than T_r and T_e ($p<0.01$). Facial and neck T_{sk} readings increased, with changes ranging from 2° to 5°C. Thirty seconds after ice application, T_r, T_e, and T_{ty} continued to increase slightly, while facial and neck T_{sk} decreased significantly. Significant differences remained between T_{ty} and T_r ($p<0.01$) and between T_{ty} and T_e ($p<0.01$).

Exercise at 48° to 51°C (condition C) resulted in increased temperatures at all sites. T_{ty} readings remained consistently higher than T_r and T_e ($p<0.01$). T_{ty} and T_{sk} readings demonstrated almost parallel behavior as exercise progressed. Once ice was applied, both T_{ty} and T_{sk} decreased; however, the differences in temperature between the two sites widened considerably ($p<0.01$). The ice had minimal effect on T_r and T_e.

After subjects exited the climatic chamber (condition D), T_e and T_{ty} readings decreased, but only T_{ty} decreased significantly. T_r, however, continued to rise. Significant differences still remained between T_r and T_{ty} ($p<0.01$) and between T_e and T_{ty} ($p<0.01$).

Table 2 shows mean temperatures for the four subjects exposed to the fan after they exited the chamber. These subjects demonstrated temperature decreases at all sites; however, T_r and

T_e changes were not statistically significant. Temperature recordings, from the termination of exercise, showed 0.6°C and 0.5°C decreases in T_r and T_e, respectively. However, significant changes occurred in both T_{ty} recordings ($T_{ty\text{-}left}$ decreased 2.4°C, and $T_{ty\text{-}right}$ decreased 1.8°C).

TABLE 2

CONDITION	T_r	T_e	T_{ty}-left	T_{ty}-right
Termination of Exercise	37.4 ± 0.3	37.7 ± 0.1	38.4 ± 0.2	38.5 ± 0.3
Exiting Chamber	37.3 ± 0.7	37.5 ± 0.1	(*)	(*)
2 min Post Chamber	37.3 ± 0.7	37.3 ± 0.2	36.8 ± 0.1	36.9 ± 0.3
4 min Post Chamber(**)	36.8 ± 1.3	37.2 ± 0.4	36.0 ± 0.4	36.7 ± 0.2

(*) No reading taken
(**) n = 3
Mean ± SD

DISCUSSION

The purpose of this study was to determine the relationship between T_{ty}, T_r, and T_e in high heat, localized cooling and heating, and exercise conditions. In comparing the temperature responses, another objective was to determine if T_{ty}, as measured by an infrared recorder, could accurately monitor thermal strain under environmentally and physically stressful conditions.

Prior to entering the climatic chamber, T_r, T_e, and T_{ty} remained constant while subjects were seated in room temperature for 20 min. These findings are similar to previous studies (Green, Danzel, & Praszkier, 1989; Shinozake, Deane, & Perkins, 1988) showing stable core temperature readings, relative to a stable environment. When skin was heated or cooled, T_{ty} did not change when recorded within 30 sec of removing the thermal stress (i.e., cold and heat applications). Other studies have reported changes in T_{ty} after facial/head cooling and heating (Marcus, 1973b; McCaffrey, 1975). However, these changes were detected after 2 min had passed following the removal of the cold and heat applications. A possible explanation for the lack of agreement with previous findings is that in the present study, the temperatures were recorded too early to detect

changes in T_{ty}. (In subsequent studies, we have recorded drops in T_{ty} after 1 to 2 min of ice application to the face.)

When subjects were exposed to hot temperatures (48° to 51°C), noticeable differences occurred among the temperature sites. In condition B, the T_{sk} demonstrated a sharp increase and remained significantly higher than temperatures at all other sites. T_{sk} was driven upward in the hot environment, possibly due to the radiant lamps. When T_{sk} increases in a hot environment, skin blood flow increases to transfer heat to the body surface (Brengelmann, 1989). However, when T_{sk} rises above core temperature, body heat storage increases because the high skin blood flow is relatively ineffective in promoting heat transfer.

Since the dorsal surface of the thermocouples is moderately conductive, the higher T_{sk} indicates that environmental factors (higher air temperature, radiant lamps, minimal convective air movement) could promote excessive body heat gain. This convective heat gain explains the gradual rise in T_r and T_e. However, T_{ty} increased faster compared to T_r and T_e, and throughout condition B, the T_{ty} readings were significantly higher than T_r and T_e. Marcus (1973a) demonstrated similar behavior when subjects were exposed to extreme temperatures caused by radiant heat. He concluded that the radiant heat to the face and head raised T_{ty}. Thus, using T_{ty} to determine body core temperature, when exposed to similar environments (e.g., desert), could lead to error. It is therefore possible that the extreme air and radiant temperatures in the present study had a significant effect on T_{ty} readings.

Exercise in the heat further promoted body heat gain, as evidenced by continual increases in T_r, T_e, and T_{ty}. Although sweat rate increases with exercise, air movement across the skin influences the degree of evaporative cooling. In the present study, the convective air movement was minimal in the climatic chamber and blunted the degree of evaporation. As expected the convective air movements had a significant effect on all temperature sites.

While subjects were seated in the climatic chamber, cooling the face and neck had no effect on increases in T_r, T_e, and T_{ty}. However, the facial and neck cooling during the exercise condition demonstrated significant decreases only in T_{ty}. Marcus (1973b) demonstrated a similar decrease in T_{ty} when cold modules were applied close to the upper margins of the ear. In addition, a more recent heat stress study indicates that vascular convection of the cooled peripheral blood vessels to the arterial supply of the tympanum causes a drop in T_{ty} (Cabanac, Germain, & Brinnel, 1987). Therefore, the effect of localized ice applications on T_{ty}, suggest a greater sensitivity of T_{ty} to peripheral cooling of the skin of the face and neck.

Upon exiting the climatic chamber, subjects were exposed to a 26° to 31°C decrease in ambient temperature, as well as an increase in the ambient convective air movements. As shown in Table 2, the dramatic environmental change appears to have had a greater impact on the 4 subjects who were exposed to the fan. Within 4 min of exiting the chamber, they demonstrated decreases of 1.8° in $T_{ty\text{-left}}$, 2.4°C in $T_{ty\text{-right}}$, and 0.6° and 0.5°C in T_r and T_e, respectively. These four subjects exited the climatic chamber immediately after termination of exercise and were still noticeably sweating. Previous studies (Narebski, 1985; Nielsen, 1988) have shown that evaporative cooling is enhanced under conditions of increased skin blood flow and sweating. This effect is further enhanced by increased air movements. As shown in Table 1, the 7 subjects who were monitored at 10 min after exiting the chamber demonstrated dramatic decreases in T_{ty}, however, T_r continued to gradually rise. This effect was probably due to the leg exercise which increased heat production in the leg muscles and venous blood to the pelvic basin.

Overall, these data suggest that measurements made with infrared thermometry are inconsistent with those reported in the thermoregulatory physiology literature. The inability of the infrared device to record drops in T_{ty} with facial cooling in both the control or heat stress condition suggests either: (1) a technical problem with the system, or (2) an operator problem. Because the device is self-calibrating and gave consistent responses when exposed to inanimate objects, the system probably was operating normally.

The operator responsible for all the measurements had extensive experience with infrared devices. Therefore, it must be concluded that the T_{ty} was taken too soon after application of heat or cold stimulus, since in previous studies (Marcus, 1973b; McCaffrey, 1975), there was a change in T_{ty} with facial/neck cooling and heating.

The ease of using T_{ty} to monitor core temperature in the field must be tempered by the fact that it may give misleading high temperature readings, and possibly lead to inappropriate clinical treatment. For example, when subjects were in the chamber, T_{ty} of 38.5°C were recorded whereas T_r and T_e were in normal range. In a field situation, such a temperature would warrant some form of cooling because 39°C is considered to be the clinical definition of hyperthermia. However, when the same subjects were cooled by ambient environment outside the chamber, and/or exposed to the fan, T_{ty} fell precipitously (T_{ty} decreases of 2.0°C in 10 min and 2.0°C in 4 min). Such a precipitous fall in temperature would prompt some form of clinical rewarming. In both of these scenarios, T_r and T_e did not demonstrate any wide fluctuation. However, core temperature does not fall precipitously in either hot or cold stress situations since thermoregulatory responses are designed to minimize such fluctuations.

Clinical treatment of heat-stressed patients is dependent on an accurate measure of core temperature. The utilization of a thermal monitoring system that is sensitive to changes in skin temperature is imperfect. In most cases, since the clinician cannot wait for unnecessary delays, the treatment is based on limited measurements. Using infrared thermometry to measure T_{ty} may produce misleading values that lead to inappropriate treatment of heat-stressed patients. Its use by clinicians in the field to evaluate heat-stress of military personnel is not encouraged.

CONCLUSION

In conclusion, these data suggest that T_{ty} can adequately measure core temperature in normothermic situations. However, significant differences between T_{ty} and traditional body core temperature sites (T_r and T_e) were observed in high heat and exercise conditions. T_r and T_e demonstrated gradual increases and decreases in direct relationship to changing environmental conditions. T_{ty}, on the other hand, appeared to be sensitive to a number of variables, including

changes in air and radiant temperature and convective air movements which influenced skin temperature. The dramatic changes in T_{ty} would suggest that the tympanum is an unpredictable site for recording body core temperature in an uncontrolled setting, particularly in high-heat environments (e.g., desert) in which subjects are sweating and are exposed to wind currents. In addition, rapidly changing environmental surroundings could produce erroneous body core temperature measurements using T_{ty}, possibly prompting undue clinical treatment or delaying essential clinical treatment.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE May 1994	3. REPORT TYPE AND DATE COVERED Final, 1990-1991

4. TITLE AND SUBTITLE
Evaluation of Infared Thermometry of Tympanic Cavity as an Indicator of Core Temperature

5. FUNDING NUMBERS
Program Element:
Work Unit Number: NSWC.WR .059 Reimbursable

6. AUTHOR(S)
Tracy Sopchick, Daniel W. Trone, & Robert S. Pozos

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Health Research Center
P. O. Box 85122
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8. PERFORMING ORGANIZATION
Report No. 94-3

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Medical Research and Development Command
National Naval Medical Center
Building 1, Tower 2
Bethesda, MD 20889-5044

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This study examined relationships among rectal (T_r), esophageal (T_e), and tympanic (T_{ty}) membrane (left and right) responses during exercise in high ambient temperatures. T_r, T_e, T_{ty}, and skin (T_{sk}) temperatures were recorded on 11 subjects under the following conditions: (A) at rest in room temperature (20 to 22°C); (B) at rest in a climatic chamber (48 to 51°C); (C) cycle ergometry exercise at 100W in a climatic chamber (48 to 51°C); and (D) at rest in room temperature (20 to 22°C). In conditions A, B and C, ice was applied to the face and neck for 1-min intervals. In condition D, four of the subjects were exposed to air currents. In condition A, T_{ty} correlated with T_r and T_e, whereas in conditions B and C, T_{ty} remained consistently higher than at all other temperature sites. During condition C, only T_{ty} and T_{sk} decreased in response to ice application. In condition D, exposure to a fan resulted in temperature decreases at all sites; however, the only significant changes were observed in T_{ty}. The T_{ty} fluctuations suggest that the tympanic membrane is an unstable measurement site in high heat and exercise conditions, as well as in changing environmental conditions.

14. SUBJECT TERMS
Tympanic; Infrared Thermometry; Core temperature; Heat stress

15. NUMBER OF PAGES
15

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited